Studies on Impingement Effects of Low Density Jets on Surfaces - Determination of Shear Stress and Normal Pressure

Sarith.P.Sathian and Job Kurian

Department of Aerospace Engineering, Indian Institute of Technology Madras
IIT Madras.P.O, Chennai 600 036, India.

Abstract. This paper presents the results of the Laser Reflection Method (LRM) for the determination of shear stress due to impingement of low-density free jets on flat plate. For thin oil film moving under the action of aerodynamic boundary layer the shear stress at the air-oil interface is equal to the shear stress between the surface and air. A direct and dynamic measurement of the oil film slope is measured using a position sensing detector (PSD). The thinning rate of oil film is directly measured which is the major advantage of the LRM over LISF method. From the oil film slope history, direct calculation of the shear stress is done using a three-point formula. For the full range of experiment conditions Knudsen numbers varied till the continuum limit of the transition regime. The shear stress values for low-density flows in the transition regime are thus obtained using LRM and the measured values of shear show fair agreement with those obtained by other methods. Results of the normal pressure measurements on a flat plate in low-density jets by using thermistors as pressure sensors are also presented in the paper. The normal pressure profiles obtained show the characteristic features of Newtonian impact theory for hypersonic flows.

INTRODUCTION

The highly under-expanded low-density free jets are typical of satellite attitude control thruster plumes. Because of the very low external pressures encountered, these plumes expand to very large solid angles and may impinge upon the external surfaces of the satellite resulting in unknown effects including shear stresses [1]. The determination of shear stress due to impingement of low density flows is essential as described the review on plume impingement [2]. The expansion of the plume creates a flow field with different levels of rarefaction, i.e., continuum, transition and finally free molecular [3]. In a detailed experimental study of low-density free jets at different pressure ratios and for low and high Reynolds numbers using a convergent-divergent nozzle of large area ratio in a low-density wind tunnel, shocks were not observed in low Reynolds number flows, suggesting that the flow might have been frozen right from the nozzle exit [4]. The transition regime of flow is an analytically complicated region where experimental methods are much suitable. Only very few experimental results [5] are available for the shear stress in the transition regime. The main objective of the present work was to implement the LRM for shear stress measurements in the transition regime for a typical plume impingement situation.

The feasibility of measuring the skin friction from the movement of a thin oil film under the action of the shear stresse in continuum flows was realized long back. It was also established that under constant skin friction, the oil film takes the shape of a wedge of varying slope with time [6]. The skin friction was calculated from the time dependent variation of the oil film thickness. The Laser Interferometric Skin Friction (LISF) technique was thus developed and is more widespread. The detailed analysis of the LISF method for continuum flows (both compressible and incompressible) has been conducted by various researchers [7], [8], [9]. The LISF method has been implemented [10] for low density shear stress determination and the results have been compared with that of [5]. A reflection type skin friction meter has been developed for incompressible flat plate turbulent boundary layers [11]. The implementation of LRM in the present work is quite similar in concept [11] except for the fact that flow field varied from continuum to rarefied in the present case. Normal pressure distribution over the model surface for different stagnation pressures shows a general distribution of pressure, which may be analysed on the basis of

CP762, *Rarefied Gas Dynamics: 24th International Symposium,* edited by M. Capitelli

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **13 JUL 2005**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE **Studies on Impingement Effects of Low Density Jets on Surfaces - Determination of Shear Stress and Normal Pressure**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Department of Aerospace Engineering, Indian Institute of Technology Madras IIT Madras.P.O, Chennai 600 036, India.**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001792, International Symposium on Rarefied Gas Dynamics (24th) Held in Monopoli (Bari), Italy on 10-16 July 2004. , The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**UU**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Newtonian impact theory [12]. The interpretations in [13] are also found extremely useful for the analysis of the normal pressure measurements from the present study.

EXPERIMENTAL PROCEDURE.

Experiments were conducted using the Rarefied Gas Dynamics facility of IIT Madras. It is a continuously run low-density wind tunnel capable of maintaining vacuum down to 10^{-5} Torr. It is divided in to upstream stagnation chamber and downstream low pressure chamber. In the facility it is possible to maintain different ratios of stagnation (Po) to downstream (Pc) pressure. The pressure in the upstream stagnation chamber is measured using Edwards Linear Active Pirani gauge (Model APGX-M-NW16AL) and a mechanical vacuum gauge (Wallace and Tiernan, Model 62A-3B). The downstream pressure is measured using MKS Baratron(Model 220CA, Model 220B) and Edwards Wide Range gauge(Model WRG-SNW25).The nozzle used was a scaled up version of a typical 0. 5N ERNO thruster rocket nozzle and is fixed on the dividing flange between the two chambers

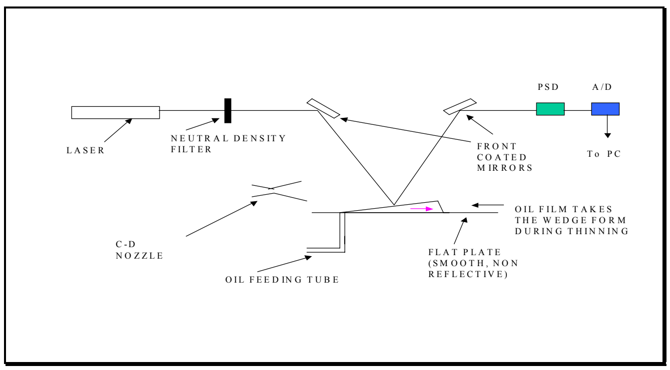

FIGURE 1. Schematic of Laser Reflection Method

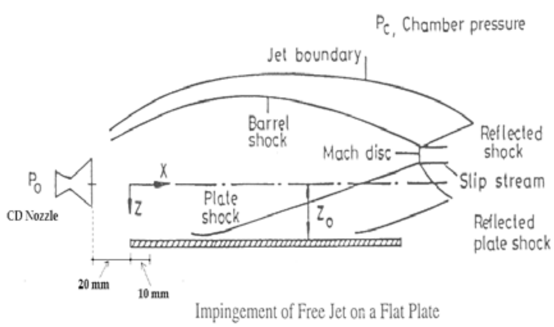

FIGURE 2. Impingement of a Free Jet on the Flat Plate

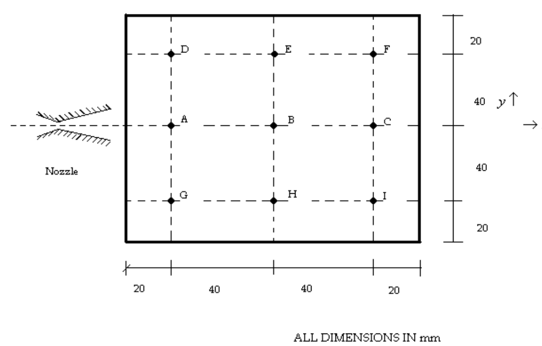

FIGURE 3. Arrangement of Thermistors on the Plate

A schematic of the LRM is given in Figure.1. It has been shown analytically that the slope characteristics of a thin oil film lying in contact with a surface on which an aerodynamic boundary layer is developing is explicitly related to the local skin friction. For all practical purposes, this thin film sticks to the surface resulting in the fact that the shear stress at the air-oil interface is also the wall shear stress of the boundary layer. The oil film attains the shape of a wedge of slope θ under the influence of shear stress. A control volume analysis shows that the slope of the oil-film (θ) is inversely proportional to time (t) as is given by the following equation.

$$\theta t = \mu / \tau = \text{constant} \tag{1}$$

where μ is oil viscosity and τ is the shear stress at oil-air interface.

LRM relies on the fact that the position of the reflected beam of light from the top surface of the oil film applied on a non-reflective but smooth plate continuously changes with time with the local thinning of the oil film. Direct and dynamic measurements of the oil film slope have been done by directing a reflected beam of laser light off the top surface of a very thin oil film to a very sensitive one-dimensional position sensitive detector (PSD). The anodised aluminium plate, which satisfied the requirement of a smooth but non-reflective surface, was kept at a distance (Zo) of 10mm below the nozzle centreline axis. The measurement point on the plate was at distance of 30mm from the nozzle exit plane. The Dow Corning 200 series silicone oil with viscosity of 350cs was used for creating the necessary oil film over the plate surface. An oil feeding mechanism was employed for the controlled flow of oil during the time of experiments. For the coherent beam of light, a 10 mW He-Ne laser was used. A neutral density filter of reflective type reduced the power of laser to 5mW. The one dimensional linear PSD (model 1LSU30, Sitek Electro Optics, Sweden) was kept outside the tunnel in such a way that the reflected laser beam, from the 10mW He-Ne laser source, from the oil film surface moves its position over the PSD. The output from the PSD was fed to an amplifier circuit through a pre-amplifier card. The amplified signals are then sent to the A/D converter (CONTEC AD 12-16U (PC) EH) housed inside a PC. A software routine has been developed to extract this digitized voltage to corresponding position data. Another software routine creates the slope history of the oil film from this position data by comparing with the calibration curve for the PSD.

The oil film slope history thus obtained is of the shape of rectangular hyperbola, from which the shear stress is determined by using a three-point formula. The LRM, over the other methods, has many advantages like elimination of bad records, absolute in nature and elimination of errors due to non-reflectivity of surface used.

Normal pressure measurements were conducted to evaluate the normal impingement force by the low density jets on the flat plate. The low density free jet emanating from the nozzle is allowed to hit on the plate surface kept at the same vertical distance (Z_0 =10mm) from the nozzle centerline axis. The horizontal distance from plate edge to the nozzle exit plane is 20mm.The matched pairs thermistors(Model G128, Fenwal Electronics, USA) used for the surface pressure measurements were calibrated using another vacuum pumping system. Nine thermistors are connected to different locations on the plate. Figure 3 shows the axial position of the plate vis-à-vis the nozzle inside the low-density tunnel and the dimensions of the plate. The letters A, B, C etc., represent thermistors locations on the plate surface. For the measurement of pressure each of the thermistors kept in the vacuum chamber has a matched one corresponding to it kept at the atmospheric pressure. Each such pair forms the two legs of a Wheatstone's bridge circuit. The voltage produced by the bridge circuit imbalance is amplified and read using a digital multimeter (Model 7150, SOLATRON). The plate is connected to the traverse mechanism powered by stepper motors. This facilitates the movement of the plate in the horizontal plane; both in x and y directions.

RESULTS AND CONCLUSIONS

Measurement of shear stress was carried out under different operating pressure ratios by varying the stagnation pressures in the upstream chamber from 10 to 120 Torr. The position of the plate was kept fixed for the present sets of experiments. Throughout the experiments pressure inside the tunnel was monitored continuously. The Knudsen numbers were in the range 0.516 to 0.028, which are well within the transition regime. The Reynolds numbers varied from 22 to 227. The run condition signal output from the LRM, which indicates the slope history of oil film, for typical flow conditions are given Figure 4. The measurements were repeated several times till similar trends are achieved for each stagnation conditions. A confidence level of 15 % is obtained for the shear stress values. The variation of the normalised shear stress $[(\tau/Po)(Zo/r^*)^2]$ with stagnation pressure Po is given in Figure 6. Only very few attempts have been made on the determination of shear stress in low density flows. Comparison of the results from the present study is done with the available results. The experimental values from the present study are compared with the results from [5] and [10](see Figure 7). In [5], experiments were conducted using two balances, which measured the pressure and tangential force on floating elements to the impingement plate. The results from these experiments were compared with Boynton's analytical plume model. But in the overlapping region of the experimental parameters, useful result was restricted to only two measurement points. Even though it matches reasonably well for the lower stagnation pressure region, appreciable difference is observed for pressures around 150 Torr. Results from [10] are also included in Figure.6 for comparison. In this case the measurement technique employed was LISF. The tunnel conditions, nozzle dimensions etc. remained the same. For similar configuration, this is the only other available result for shear stress in the transition regime. The LISF results showed similar variation of shear stress with stagnation pressure. But for certain values of stagnation conditions appreciable variations are observed. But in all cases the shear stress values steadily increase towards the continuum regime of flow [see Figure 5 (b)]. Its variation with Kn is given in Figure 5 (a). These results are quite acceptable. With increase in stagnation pressure, the jet size increases and the flow field is more towards the continuum regime where shear stress values undergo order of magnitude changes.

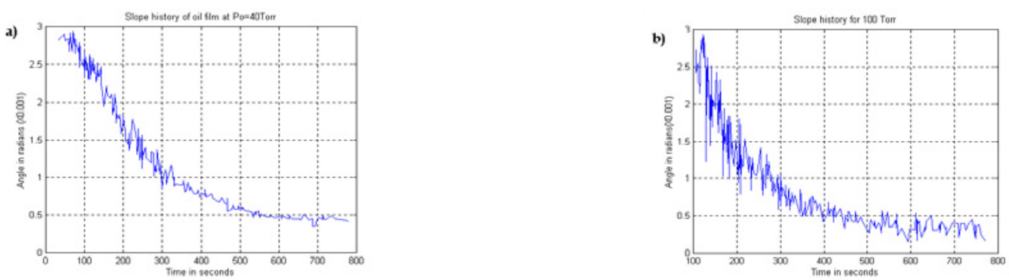

FIGURE 4. LRM signal for different stagnation pressures a) Po = 40 Torr and b) Po =100 Torr

FIGURE 5. Variation of shear stress with a) Knudsen number, Kn and b) Stagnation pressure, Po.

The normal pressures due to impingement were measured for different pressure ratios at the spatial locations and is shown in Figure 7 a), b) and c). The measured normal pressure values, using thermistors, are fitted to a grid surface in the three-dimensional space, which is obtained by cubic interpolation. Newtonian theory, even though it assumes the ideal fluid flow, gives fairly acceptable results for pressure distributions over hypersonic bodies in air. The applicability of the Newtonian flow concepts has been verified successfully through numerous practical implementations. For the plumes impinging on a surface, a maximum value of pressure will be present, which is the peak pressure obtained in normal pressure measurement.

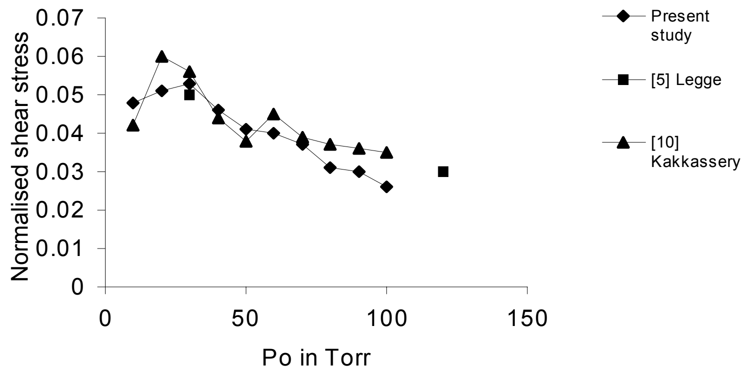

FIGURE 6. Variation of Normalised shear stress and comparison with available results

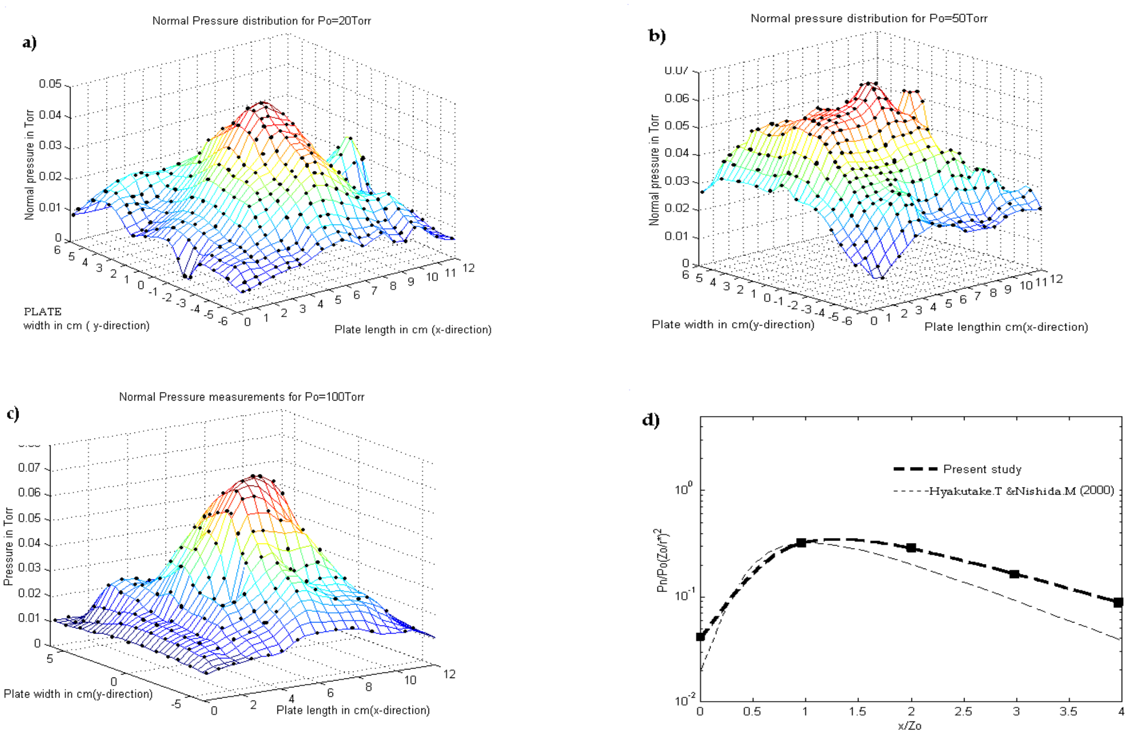

FIGURE 7. Normal pressure distributions on the plate for stagnation pressures a) 20 Torr. b) 50 Torr. c) 100 Torr. d) Normalised Pressure Profiles for Normal Pressure Distribution on Flat Plate and comparison.

In the actual case the peak pressure lies inside the plume boundary. For a plume expanding to very low ambient pressure, velocity approaches a limiting value rather quickly. The density on the other hand decreases rather rapidly near the plume boundary. So the momentum flux normal to the surface will begin decreasing somewhere inside the plume boundary. The Newtonian pressure distribution from the impingement curve predicts rapid increase of pressure till it reaches a peak value. The pressure then decreases gradually along the longitudinal direction. In the present study a similar behaviour is observed particularly for higher stagnation pressures. The possibility of oblique shocks at the plume boundary-plate intersection point, mainly for lower pressure ratios, has been indicated in [13]. Relatively irregular distribution of normal pressure is observed for lower stagnation pressure free jets in the present study. More than one pressure peak may exist for much lower stagnation pressures. Moreover the pressure distribution is appreciably different from that of higher stagnation pressures. As noted in [12], the normal pressure profiles of lower stagnation pressures show a tendency to deviate from the Newtonian pressure distribution. For a variety of reasons, possibly associated with plume/model surface and plume chamber pumping interactions the normal pressure distribution for flows well downstream of the nozzle exit has been found asymmetrical about the nozzle centreline. But for higher-pressure ratios the normal pressure distribution is more symmetrical. Experimental data on normal pressure distributions under the conditions of parallel impingements of plumes on flat plates are currently not available from literature. Computational studies using DSMC on a similar physical model has been explained in [14]. The normalized pressure profiles of the normal pressure distributions from the DSMC simulations are compared with that obtained from the present experiments [see Figure 7.d)]. For the similar experimental conditions, these pressure profiles, i.e., from the present experiments and from DSMC computations show a similar trend. Such comparisons with the experiments can help the ongoing computational efforts by providing experimental data for validating the DSMC models.

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